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UCRL- 84252
PREPRINT
CONF-800441--2

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# CURRENT RESULTS OF THE TANDEM MIRROR EXPERIMENT

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This paper was prepared for inclusion in the Proceedings of the International Symposium on Physics and Open-Ended Fusion Systems, to be held at the University of Tsukuba, Tsukuba, Japan April 15 - 18, 1980

April 9, 1980

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# Current Results of the TMX Experiment*

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Abstract: The basic operating characteristics of the Tandem Mirror Experiment, (TMX) at the Lawrence Livermore Laboratory in the USA have been established. Tandem-mirror plasmas have been produced using neutral-beam-fueled end plugs and a gas-fueled center cell. An axial potential well between the end plugs has been measured. There is direct evidence that this potential well enhances the axial confinement of the center-cell ions. The observed densities and loss currents are consistent with preliminary studies of the particle sources and losses near the magnetic axis. The observed confinement is consistent with theory when plasma fluctuations are low. When the requirement of drift-cyclotron loss-cone mode stability is violated, the plasma fluctuations degrade the center-cell confinement.



* Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore Laboratory under Contract No. W-7405-Eng-48.

## 1. Introduction

This paper reviews the initial results of the TMX experiment, and presents our current understanding of TMX operation. In particular, we have a consistent account of the particle balance, we have improved the theory of TMX scaling, and some experimental scaling results are available. TMX is a tandem-mirror fusion-research device 1, in which two neutral-beam-fueled end plugs enhance the confinement of a center-cell plasma (Fig. 1). The center cell is fueled by deuterium gas. The end-plug plasmas are denser than the center-cell plasma, and establish an electrostatic-potential barrier which impedes the loss of center-cell ions. The baseball coils that contain the end-plug plasmas provide the magneto hydrodynamic (MHD) stability of the system.

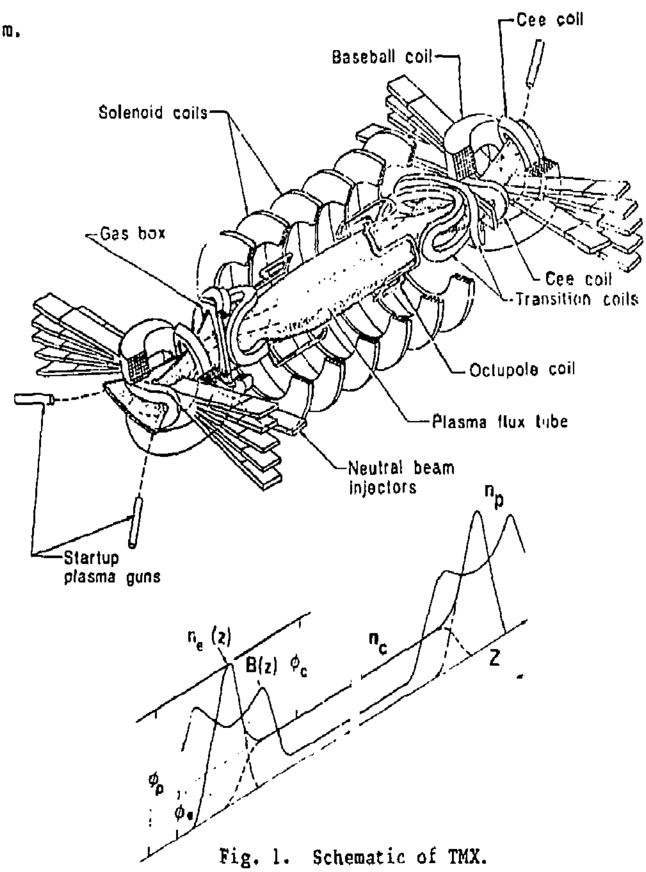



Fig. 1. Schematic of TMX.

## 2. Review of Initial TMX Results

The initial TMX experiments were performed from July through December 1979. We obtained several basic results [2]. First, tandem-mirror plasmas can be initiated and maintained in TMX. Startup plasma guns are used to provide a target plasma in the end plugs, where the neutral beams create a dense ($\leq 4 \times 10^{13}\text{cm}^{-3}$) plasma (Fig. 2). The center-cell gas feed fills and maintains the center-cell plasma. A steady-state is reached and maintained for the duration of the available neutral beam power.

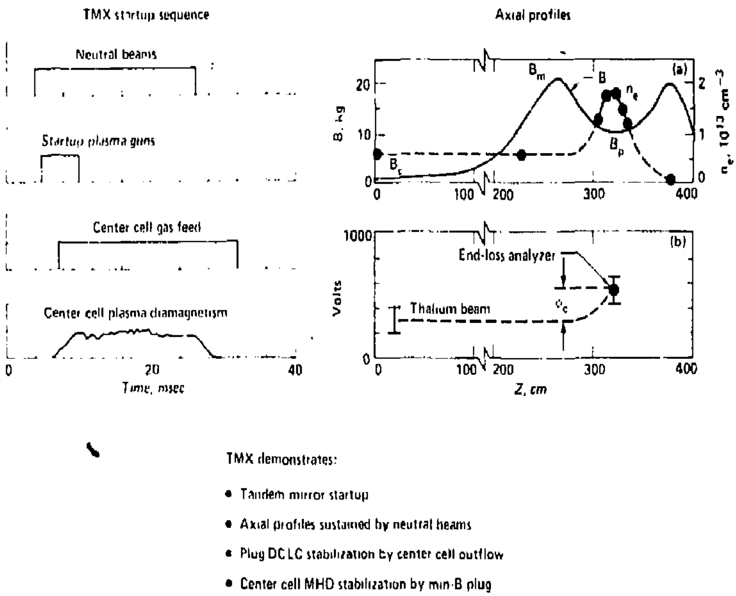



Fig. 2. TMX generates tandem mirror configuration.

Secondly, we observe finite-β plasmas ($\beta = \frac{8\pi_n kT}{B^2}$) in the center cell using an array of diamagnetic loops and a neutral-beam-attenuation diagnostic of the radial plasma profile. The center cell itself does not have MHD stability. Thus, the stable, high pressure end-plug plasmas have stabilized the system. However, we have not reached the limits set by

MHD-stability theory for the tandem mirror, because we have not heated the center-cell plasma, sufficiently.

Thirdly, the axial plasma density profile is measured using neutral-beam attenuation, microwave interferometers, and end-loss diagnostics. A tandem-mirror density profile has been established. The end-plug plasmas are a few times denser than the center-cell, ($\sim 2 \times 10^{13} cm^{-3}$ versus $\sim 5 \times 10^{12} cm^{-3}$) and the plasma density at the end wall is orders of magnitude lower (it is $10^{9}$ to $10^{10} cm^{-3}$). In addition, we have observed that the center-cell outflow can be sufficient to stabilize the drift-cyclotron-loss-cone (DCLC) in stability. The end plugs cannot be maintained without either center-cell plasma or startup plasma guns, and the end-plug density is reduced if the gas feed is too low.

Finally, TMX has demonstrated electrostatic end-plugging by a neutral-beam-fueled plasma[2]. We have measured the existence of a potential well using a Thallium-ion-beam probe to measure the center-cell potential and a gridded end-loss analyzer to measure the end-plug potential (Fig. 2). Direct evidence of electrostatic end plugging has been obtained by turning off the neutral beams that fire into one end plug (Fig. 3). After the end-plug plasma has decayed, a collisional center-cell plasma and the other end-plug plasma remain. The flow out of the center cell into the end plugs is equal because the center-cell is collisional. More loss current flows through the end-plug without a neutral-beam-fueled plasma than through the denser end-plug fueled by the neutral beams. This fact shows that end-plugging exists. An independent indication of end-plugging is the axial confinement of the center-cell plasma (along the central flux tube) when both end plugs are neutral-beam fueled. We directly measure the axial confinement. We compute the confinement expected from TMX without electrostatic end-plugging using well known theory. We have observed an axial confinement time up to nine times that

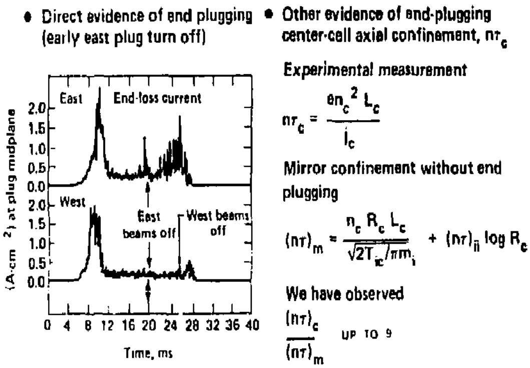


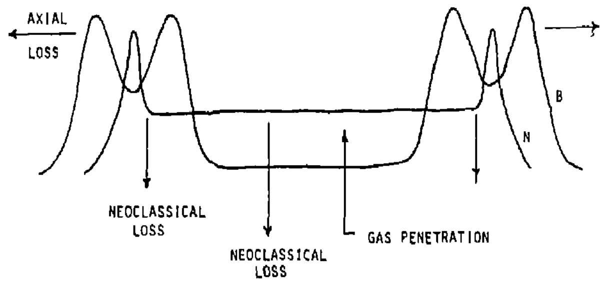

Fig. 3. *TMX electrostatic plugging improves center-cell confinement.*

expected from TMX without end-plugging. The end-plugging is electrostatic and is not "RF plugging," because we observe that plasma fluctuations degrade the center-cell confinement.

## 3. Particle Balance in TMX

The total axial loss current observed from the central flux tube of TMX depends upon several processes (Fig. 4). These processes change when the neutral beams fueling one end plug are turned off. There are axial losses and radial losses predicted by neoclassical theory. Gas penetration provides the particle source. The axial losses are directly measured. They depend upon classical processes and the plasma fluctuations, as described below.

Radial losses are expected due to magnetic drifts. At the core of the plasma in the center cell these losses are negligible. The low energy ions trapped in the end plug (Yushmanov ions) may be lost quickly as suggested by Ryutov, but the maximum losses of this type are usually small compared to axial losses.




AXIAL LOSS: MEASURED BY END-LOSS ANALYZER

RADIAL LOSS: ESTIMATED FROM NEOCLASSICAL THEORY

- LOSSES IN CENTER CELL
- LOSS OF YUSHMANOV IONS IN PLUG

IONIZED SOURCE: ESTIMATED USING COMPUTER CODE

- MULTIPLE CHARGE EXCHANGE PENETRATION
- RADIAL PROFILES AFFECT RESULTS
- WALL REFLECTION IS IMPORTANT
- AFTER EAST PLUG TURNOFF THE SOURCE ON AXIS INCREASES DUE TO MEASURED DECREASE IN ELECTRON TEMPERATURE AND RADIUS

IONIZED NEUTRAL BEAM: NEGLIGIBLE COMPARED TO CENTER-CELL FUELING

Fig. 4. TMX central-flux-tube losses and sources.

Neutral atoms are ionized at the core of the center-cell plasma. This is the source that must balance the losses. $D_2$ gas strikes the plasma oundary but does not penetrate to the core. We have begun to study the fueling of the center-cell plasma using a computer model developed by G. E. Gryczkowski. The neutral atoms ionized at the core of the center-cell plasma are the result of several successive charge-exchange events. The amount of ionization deep within the plasma is sensitive to the plasma densities and temperatures, and also to the probable reflection of neutral atoms by the radial walls of the center cell vacuum chamber. After one end plug is turned off, the electron temperature is lower and the center-cell plasma is smaller. This enhances the source of ions near the machine axis. The ionized neutral beam current is negligible compared to the ionized neutral current in the center cell.

A comparison of sources and losses in TMX is shown in Fig. 5. The current, normalized to the end-plug midplane, is plotted as a function of center-cell density. This data was obtained by varying the amount of neutral-beam current fueling the end plugs. The plasma fluctuations and the center-cell confinement changed substantially, as is discussed below. The predicted gas penetration is shown in the limits of no wall reflection and total wall reflection. The observed axial losses lie between these limits. The estimated radial losses are a small correction, but do group the total estimated losses more tightly. After the decay of one end-plug plasma, both the predicted source and the observed losses increase. We are working to refine this model and to obtain better data, including better radial profiles.

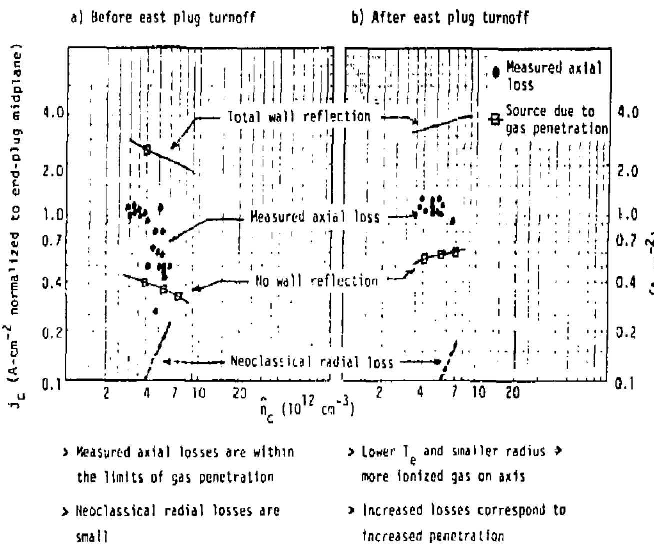



Fig. 5. Comparison of central-flux-tube sources and losses in TMX.

## 4. TMX Scaling Experiments

We are beginning to understand the scalings which might be observed experimentally in TMX (Fig. 6). We must establish a potential well to confine the center-cell plasma, and this requires an end plug to center-cell density ratio ($n_p/n_c$) greater than one; but we must also satisfy the DCLC stability requirement. The current flowing through the end plug must modify the energy distribution at the end-plug midplane to stabilize the plasma. We calculate this loss current using present theory. This required current imposes an upper limit on center-cell confinement, which is a decreasing function of $n_p/n_c$. In contrast, electrostatic confinement is an increasing function of ($n_p/n_c$). The approximate limit at which both classical confinement and end-plug stability are expected is a density ratio of three. Unstable behavior is expected at larger density ratios.

- Limitations

  Electrostatic confinement requires $\phi_c > 0$

  $\Rightarrow n_p/n_c > 1$

  Center-cell losses must provide DCLC stabilization of end plugs

  $$j_{stab}(\mathrm{A \cdot cm^{-2}\ per\ end}) = \frac{c n_p \phi_{pm}^{3/2}}{E_p (R_p - 1) M_i^{1/2}} \left(\frac{r_p}{a_i}\right)^{-4/3} \quad \text{(cm, keV, AMU)}$$

  $c \simeq 3.8 \times 10^{-12}$

- To obtain stable operation

  $$(n\tau)_{classical} \leq (n\tau)_{stab} = \frac{e n_c^2 L_c R_c / 2}{2 j_{stab}}$$

  $$(n\tau)_{classical} = \left(10^{11} T_{ic}^{1/2} \phi_c + \frac{n_c L_c R_c}{\sqrt{8 T_{ic}/\pi m_i}}\right) \exp \frac{\phi_c}{T_{ic}}$$

  $$\Rightarrow \frac{n_p}{n_c} \lesssim 3 \text{ for TMX at present}$$

- Implied operating range

  $$1 \leq \frac{(n\tau)_c}{(n\tau)_m} \lesssim 10 \text{ for } T_{ep} = 0.15 \text{ keV}$$

  $T_{ic} = 0.08$ keV

  No thermal barrier

Fig. 6. TMX operating range.

We have obtained some data demonstrating this effect (Fig. 7). The neutral beam current was increased while maintaining a fixed center-cell gas feed. The center-cell plasma fluctuations increased an order of magnitude, as $n_p/n_c$ increased from three to seven. When the plasma fluctuations were low, the observed axial confinement was classical and significantly exceeded the confinement expected without electrostatic end plugging. As the plasma fluctuations increased, the observed confinement decreased. This decrease is consistent with the recent theory of Matsuda and Rognlein[3] describing the effects of plasma fluctuations on center-cell confinement. We are now trying to understand the detailed scaling in this unstable regime, and to extend the stable range of operation of TMX.

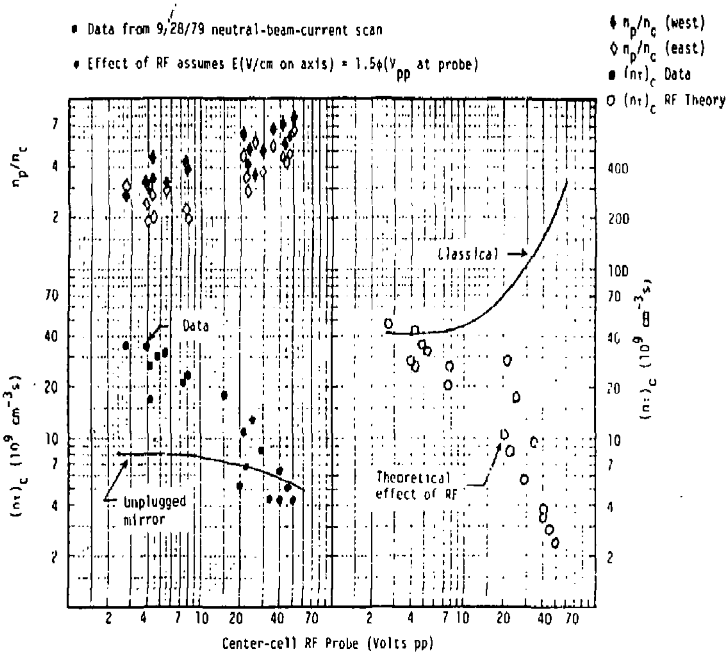



Fig. 7. TMX plasma fluctuations degrade center-cell confinement.

## 7. Acknowledgements

The entire TMX scientific and technical staff contributed to this work. Particular thanks are due D. E. Baldwin, T. A. Casper, J. F. Clauser, F. H. Coensgen, D. L. Correll, J. C. Davis, J. H. Foote, R. J. Fortner, A. H. Futch, R. K. Goodman, D. P. Grubb, G. A. Hallock, R. S. Hornady, A. L. Hunt, C. V. Karmendy, B. G. Logan, Y. Matsuda, R. H. Munger, W. E. Nexsen, P. Poulsen, T. D. Rognlien, T. C. Simonen, D. R. Slaughter, B. W. Stallard and O. T. Strand.

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